

Self Consistent Models of the Solar Wind

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Abstract The origins of the hot solar corona and the supersonically expanding solar wind are still the subject of much debate. This paper summarizes some of the essential ingredients of realistic and self-consistent models of solar wind acceleration. It also outlines the major issues in the recent debate over what physical processes dominate the mass, momentum, and energy balance in the accelerating wind. A key obstacle in the way of producing realistic simulations of the Sun-heliosphere system is the lack of a physically motivated way of specifying the coronal heating rate. Recent models that assume the energy comes from Alfvén waves that are partially reflected, and then dissipated by magnetohydrodynamic turbulence, have been found to reproduce many of the observed features of the solar wind. This paper discusses results from these models, including detailed comparisons with measured plasma properties as a function of solar wind speed. Some suggestions are also given for future work that could answer the many remaining questions about coronal heating and solar wind acceleration.

Keywords solar corona · solar wind · turbulence · waves

1 Introduction

It has been known since the early part of the twentieth century that the temperature in the Sun's outer atmosphere undergoes a rapid inversion, from a relatively cool ($T < 10^4$ K) photosphere and chromosphere to a hot and ionized ($T > 10^6$ K) corona. Since the dawn of the space age, coronal heating has also been known to be linked to the acceleration of a plasma outflow that reaches speeds of 300–800 km s⁻¹ in interplanetary space. In the years since the twin problems of coronal heating and solar wind acceleration were formulated, many physical processes have been suggested to be responsible. Only a small fraction of the mechanical energy in the Sun's sub-photospheric convection zone needs to be converted to heat in order to power the corona. However, it has proved exceedingly difficult to distinguish between competing theoretical models using existing observations. Recent summaries of these

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problems and controversies have been presented by, e.g., Aschwanden (2006), Klimchuk (2006), Zurbuchen (2007), Hollweg (2008), and Cranmer (2009).

Most of the proposed physical models can be grouped into two broad paradigms. As will be seen below, the basic difference between these paradigms concerns the overall topological connectivity of the magnetic flux tubes that feed the solar wind:

1. If solar wind flux tubes are open to interplanetary space—and if they remain open on timescales comparable to the time it takes plasma to accelerate into the corona—then the main sources of energy must be injected at the footpoints of the flux tubes. Thus, in *wave/turbulence-driven (WTD) models*, the convection-driven jostling of the flux-tube footpoints is assumed to generate wave-like fluctuations that propagate up into the extended corona. These waves (usually Alfvén waves) are often proposed to partially reflect back down toward the Sun, develop into strong magnetohydrodynamic (MHD) turbulence, and dissipate gradually. These models have been shown to naturally produce realistic fast and slow wind conditions with wave amplitudes of the same order of magnitude as those observed in the corona and heliosphere (Hollweg 1986; Velli et al. 1991; Wang and Sheeley 1991; Matthaeus et al. 1999; Suzuki and Inutsuka 2006; Cranmer et al. 2007; Wang et al. 2009; Verdini et al. 2010; Matsumoto and Shibata 2010).
2. Near the Sun, all open magnetic flux tubes are observed to exist in the vicinity of closed loops that are evolving on a wide range of spatial and time scales in a complex “magnetic carpet” (Title and Schrijver 1998). Thus, it is natural to propose a class of *reconnection/loop-opening (RLO) models*, in which solar wind flux tubes are assumed to be influenced by magnetic reconnection with closed-field regions that are continuously emerging, fragmenting, and being otherwise jostled by convection. In these models the mass, momentum, and energy of the solar wind is input from loops of varying properties in the low corona. Some have suggested that RLO-type energy exchange primarily occurs on small, supergranular scales (Axford and McKenzie 1992; Fisk et al. 1999; Fisk 2003; Schwadron and McComas 2003). However, other models have been proposed in which the reconnection occurs in and between large-scale coronal streamers (Einaudi et al. 1999; Suess and Nerney 2004; Antiochos et al. 2010).

In the interest of brevity, this paper does not review the wider range of empirically based solar wind models that do not contain self-consistent coronal heating physics. These models are often quite sophisticated in their treatment of multi-fluid (e.g., Hansteen et al. 1997; Li 2003; Lie-Svendsen and Esser 2005) or multi-dimensional (e.g., Endeve et al. 2003, 2004; Roussev et al. 2003; Riley et al. 2006; Nakamizo et al. 2009) effects. However, their use of *ad hoc* rates of heating and momentum deposition places them in a separate category from the self-consistent models discussed here.

2 Essential Ingredients

Before reviewing the results of WTD or RLO models, it is useful to summarize what kinds of “physics inputs” are necessary to build a self-consistent model of solar wind acceleration.

The first models of the solar wind were not self-consistent, but they contained many valuable insights that led the way to future improvements. Parker (1958) found that a constant coronal temperature of order 10^6 K (i.e., roughly consistent with strong radial electron conduction) provides enough of an outward gas pressure gradient force to overcome gravity and produce a natural transition from a subsonic (bound, negative energy) state near

the Sun to a supersonic (escaping, positive energy) state in interplanetary space. Throughout the 1960s, new models with different prescribed coronal temperatures $T(r)$ explored the parameter space of possible time-steady solar wind solutions. Some of these models included temperatures consistent with polytropic equations of state (i.e., $P \propto \rho^\gamma$), and Holzer and Axford (1970) found that $\gamma \leq 1.5$ is necessary for an accelerating solar wind. Also, Sturrock and Hartle (1966) solved two-fluid ($T_p \neq T_e$) energy equations with heat conduction, and found that some kind of “extra” energy addition is needed in the corona to heat the plasma to the temperatures seen at 1 AU.

The order-of-magnitude amount of coronal heating that is needed to produce the solar wind can be estimated from an approximate version of the internal energy conservation equation (see, e.g., Leer et al. 1982). The time-steady version of this equation,

$$\nabla \cdot \left[\mathbf{F}_{\text{heat}} + \mathbf{F}_{\text{cond}} + \rho \mathbf{u} \left(\frac{u^2}{2} + \frac{5P}{2\rho} - \frac{GM_\odot}{r} \right) \right] = Q_{\text{rad}}, \quad (1)$$

describes the balance between an imposed heat flux (\mathbf{F}_{heat}), conduction along the magnetic field (\mathbf{F}_{cond}), radiative losses (Q_{rad}), and fluxes of kinetic energy, enthalpy, and gravitational potential energy (the three terms in parentheses). When studying how the energy budget varies from the corona to 1 AU, the dominant terms are the imposed heating, the kinetic energy flux, and gravity. Thus, Hansteen and Leer (1995) found that one can estimate

$$F_{\text{heat}} = |\mathbf{F}_{\text{heat}}| \approx (\rho u)_{\text{corona}} \left(\frac{V_{\text{esc}}^2}{2} + \frac{u_\infty^2}{2} \right) \quad (2)$$

(see also Leer and Marsch 1999; Schwadron and McComas 2003). Thus, if we can specify the mass flux in the corona, ρu , the escape velocity from the solar surface, $V_{\text{esc}} = (2GM_\odot/R_\odot)^{1/2}$, and the asymptotic, or terminal outflow speed, u_∞ , we can estimate how much heat must be deposited in the corona. Using typical values (Cranmer et al. 2007) for the fast solar wind associated with coronal holes, $F_{\text{heat}} \approx 8 \times 10^5 \text{ erg cm}^{-2} \text{ s}^{-1}$. For the slow solar wind associated with streamers and active regions, $F_{\text{heat}} \approx 3 \times 10^6 \text{ erg cm}^{-2} \text{ s}^{-1}$.

In order to go beyond order-of-magnitude estimates, models must begin to include self-consistent descriptions of specific physical processes involved in the mass, momentum, and energy conservation of accelerating plasma parcels. There are at least five essential ingredients to such a self-consistent picture of the solar wind:

1. *Physically motivated coronal heating.* The actual origin of the imposed heat flux F_{heat} (or the equivalent volumetric rate $Q_{\text{heat}} = |\nabla \cdot \mathbf{F}_{\text{heat}}|$) must be included explicitly. The key difference between the WTD and RLO paradigms, as described in the previous section, rests on whether the heating is deposited by fluctuations within an open flux tube or via impulsive injection from other surrounding flux tubes. Models can differ, of course, in the level of detail given in the self-consistent heating rates. Some descriptions of turbulence and magnetic reconnection specify only the energy that is input into the system on the largest spatial scales. These models thus employ various phenomenological assumptions about how that energy is eventually dissipated. Other models follow the detailed microphysics of the dissipation itself—usually by simulating either particle-particle collisions or wave-particle interactions.
2. *Additional momentum sources in the fast wind.* In the 1970s and 1980s, it became increasingly evident that the maximum mean plasma temperature in the open-field corona (i.e., approximately $(T_p + T_e)/2$) does not exceed $\sim 2 \times 10^6 \text{ K}$. Even the measurements of higher values of T_p in coronal holes made in the 1990s did not substantially change

this constraint on the one-fluid average (see, e.g., Kohl et al. 2006; Cranmer 2009). A solar wind with this mean temperature that is driven only by gas pressure cannot accelerate to the highest speeds ($700\text{--}800\text{ km s}^{-1}$) measured at 1 AU (Leer and Holzer 1980). MHD fluctuations have been shown to exert an additional “wave pressure” or outward ponderomotive force on the mean fluid (Dewar 1970; Belcher 1971; Ofman and Davila 1998). This appears to be a necessary component of fast-wind models, and it may even provide as much as half the acceleration in flux tubes connected to polar coronal holes (e.g., Cranmer 2004).

3. *A self-regulating mass flux.* The Sun’s mass loss rate, $\dot{M} \approx 2 \times 10^{-14} M_{\odot} \text{ yr}^{-1}$, is generally believed to be determined in the transition region by a balance between downward heat conduction, local radiative losses, and the upward enthalpy flux (Hammer 1982; Withbroe 1988; Hansteen and Leer 1995; Leer et al. 1998). Self-consistent models should not artificially fix the properties of the transition region and low corona. Instead, models should allow these properties to “float” until a natural, stable, and time-steady solution for the energy balance is found.
4. *Extended conduction and heating to 1 AU.* Even far above the corona, *in situ* measurements show that energy deposition and conductive energy transfer are still occurring (e.g., Coleman 1968). The radial gradients of the proton and electron temperatures are substantially shallower than would be the case if plasma parcels were expanding adiabatically (Marsch et al. 1983, 1989; Richardson et al. 1995). *Helios* measurements of radial growth of the proton magnetic moment between 0.3 and 1 AU (Schwartz and Marsch 1983) point to specific collisionless processes that continue to affect the energy budget far from the Sun. Recent empirical studies of the fast solar wind (Breech et al. 2009; Cranmer et al. 2009) have shown that it is important to take careful account of electron heat conduction in order to determine how the heating is partitioned between protons and electrons. Self-consistent models should be able to describe both the extended heating that is observed and the transition from collisional to collisionless conduction in the heliosphere.
5. *Funnel-type magnetic field expansion.* Most of the plasma that eventually is accelerated outwards as the solar wind seems to originate in the lanes and vertices between supergranular network cells in the chromosphere. As height increases, the strong vertical magnetic field decreases and the flux tubes expand laterally. Thus, the flux tubes become magnetic funnels that eventually merge with one another into a topologically complex “canopy” in the low corona (Gabriel 1976; Dowdy et al. 1986; Cranmer and van Ballegoijen 2005). Several semi-empirical studies of coronal heating and solar wind acceleration show that this kind of funnel-like flux tube expansion is necessary to producing realistic emission-line spectra in the transition region (e.g., Esser et al. 2005; Marsch et al. 2008; Byhring et al. 2008; Pucci et al. 2010).

The ways in which the above ingredients interact with one another to produce a time-steady solar wind are complex and nonlinear. Even though the wind flows upwards, sometimes the physics of the extended corona (e.g., heating at heights of 1–2 solar radii above the surface) can have a significant feedback on *lower* regions in the atmosphere (e.g., frozen-in charge states that are set just above the transition region). It is important for a model to allow these various pieces of physics to evolve together toward a stable steady state and not be constrained by input assumptions. For example, the lower boundary of the model should not be so high as to exclude the transition region and upper chromosphere, and the upper boundary should not be so low as to exclude the sonic or Alfvénic critical points of the flow.

3 Wave/Turbulence Models

There has been substantial work over the last few decades devoted to exploring the idea that coronal heating and solar wind acceleration may be explained as a result of the dissipation of waves and turbulent fluctuations. No matter the relative importance of reconnections and loop-openings in the low corona, we do know that waves and turbulent motions are present everywhere from the photosphere to the heliosphere (see observational summaries of Tu and Marsch 1995; Cranmer and van Ballegoijen 2005; Aschwanden 2008). Thus, it is of interest to determine how waves affect the mean state of the plasma in the absence of any other sources of energy.

Cranmer et al. (2007) described a set of WTD-type models in which the time-steady plasma properties along a one-dimensional solar wind flux tube are computed. These model flux tubes are rooted in the optically thick solar photosphere and are extended into interplanetary space. The numerical code developed in that work, called ZEPHYR, solves the one-fluid equations of mass, momentum, and energy conservation simultaneously with transport equations for Alfvén and acoustic wave energy fluxes. ZEPHYR is the first code capable of producing self-consistent solutions for the photosphere, chromosphere, corona, and heliosphere that combine: (1) shock heating driven by an empirically guided spectrum of acoustic waves, (2) extended heating from Alfvén waves that get partially reflected and then are dissipated by MHD turbulence, and (3) wind acceleration from gradients of gas pressure, acoustic wave pressure, and Alfvén wave pressure.

The only input “free parameters” to the Cranmer et al. (2007) models were the photospheric lower boundary conditions for the waves and the radial dependence of the magnetic field along the flux tube. Photospheric measurements of the horizontal motions of intergranular flux concentrations (i.e., G-band bright points having $B \sim 1.5$ kG) were used to constrain the frequency spectrum of Alfvén waves at the lower boundary (see also Nisenson et al. 2003). All models shown below used the same lower boundary conditions and differed only in the rates of flux-tube superradial expansion.

The self-consistent coronal heating in the ZEPHYR models is the result of propagating Alfvén waves being partially reflected by radial gradients in the density and magnetic field strength. It has been shown that once there are *counter-propagating* wave packets that interact with one another along a flux tube, a nonlinear turbulent cascade can then occur relatively quickly (Iroshnikov 1964; Kraichnan 1965). The energy flux in the cascade, from large to small eddies, terminates in dissipation and heating that extends from the low corona out into the heliosphere (see also Matthaeus et al. 1999; Dmitruk et al. 2002; Cranmer and van Ballegoijen 2005; Chandran and Hollweg 2009; Verdini et al. 2009, 2010; Cranmer 2010).

In addition to the properties of the waves and turbulence, there are other aspects of the models that determine how much coronal heating occurs. One of these is the radial location of the Parker “critical point.” This is the point at which the wind speed exceeds a critical speed defined by the sound speed and the MHD wave amplitudes (see, e.g., Jacques 1977). In models where the magnetic flux tubes expand purely radially, there is usually just one unique location for this critical point. However, in flux tubes that undergo super-radial expansion there are multiple possible locations where the critical point could be located. These locations correspond to local minima in a potential-energy-like quantity that was defined by Kopp and Holzer (1976) and Vázquez et al. (2003). However, only one of these points corresponds to a global energy minimum, and thus only this one critical point location gives a stable and time-steady solar wind. For some models, changing the flux-tube expansion only slightly is enough to alter the relative depths of these potential en-

ergy wells, such that the critical point *shifts abruptly* from a location close to the Sun to one much farther from the Sun. When this occurs the global momentum and energy balance of the solar wind changes abruptly as well. Early studies (e.g., Leer and Holzer 1980; Pneuman 1980) showed that high critical points—where most of the heating is in the subsonic low corona—correspond to dense and slow solar winds. Conversely, low critical points—where the heating is mainly in the supersonic outer corona—correspond to low-density and fast solar winds. For a “stretched dipole” model of the solar-minimum magnetic field, the Cranmer et al. (2007) models show precisely this kind of discontinuity between fast and slow winds at a heliospheric latitude of $\sim 20^\circ$, similar to what *Ulysses* observed (Goldstein et al. 1996).

Figure 1 shows several different comparisons between solar wind measurements and the results of the Cranmer et al. (2007) models. In all six panels the observations and models are sorted by the solar wind speed at 1 AU. In panel (a), *in situ* proton temperature data are taken from the ACE/SWEPAM online archive for the time periods between 1998 and 2005 (see also Matthaeus et al. 2006). Note that the plot juxtaposes the measured T_p values with the ZEPHYR one-fluid mean temperatures $((T_p + T_e)/2)$, so the comparison is not exact. In panel (b), the coronal superradial expansion factor defined by Wang and Sheeley (1990) is shown as a function of wind speed, along with the empirical trend of anticorrelation also demonstrated by Wang and Sheeley (1990). In panel (c), ACE proton temperatures and densities have been combined to form the specific entropy quantity that was found by Pagel et al. (2004) to correlate strongly with wind speed. In panel (d), the power in magnetic fluctuations measured by *Helios* between 0.3 and 0.5 AU by Tu et al. (1992) is compared with a similar quantity estimated from the models in the way described by Cranmer et al. (2007).

Panels (e) and (f) of Figure 1 show ion data from *Ulysses*/SWICS taken at two different phases of that mission (light gray: 1990–1994, dark gray: 1994–1995). In panel (e), the measured ratio of O^{7+} to O^{6+} number density is compared to ZEPHYR models of this “frozen in” nonequilibrium ionization state. Although the overall trend with wind speed is similar to that in the data, there is an overall shift downward in the modeled ratios. This may be due to the fact that the models assume the electron velocity distribution to be Maxwellian; i.e., the models ignore the additional ionization that would be caused by a suprathermal “electron halo” in the corona (Esser and Edgar 2000). In panel (f), the measured ratio of iron to oxygen elemental abundances—normalized to their photospheric values—is compared to models that apply the Laming (2004) idea for first-ionization-potential (FIP) fractionation. This idea utilizes the ponderomotive force exerted by Alfvén waves to accelerate ions in the partially ionized upper chromosphere, while leaving the neutrals unaffected. Note that the model results shown in panels (e) and (f) contradict the commonly held assertion that slow-wind FIP and charge-state properties can only be explained by the injection of plasma from closed-field regions on the Sun (see also Pucci et al. 2010).

Three other successful predictions of the ZEPHYR models are summarized below:

1. Recent *Hinode*/EIS measurements of strong Doppler shifts at the edges of active regions indicate outflow speeds of order 100 km s^{-1} in the coronal source regions of some slow wind streams (Harra et al. 2008; Subramanian et al. 2010). As shown in Figure 7a of Cranmer (2010), the ZEPHYR model of an active-region-associated slow wind flux tube naturally exhibits a local maximum in the outflow speed of the observed order of magnitude at heights between 0.02 and $0.1 R_\odot$ above the photosphere.
2. The original Cranmer et al. (2007) model of the fast wind associated with polar coronal holes used a magnetic field model consistent with the 1996–1997 solar minimum.

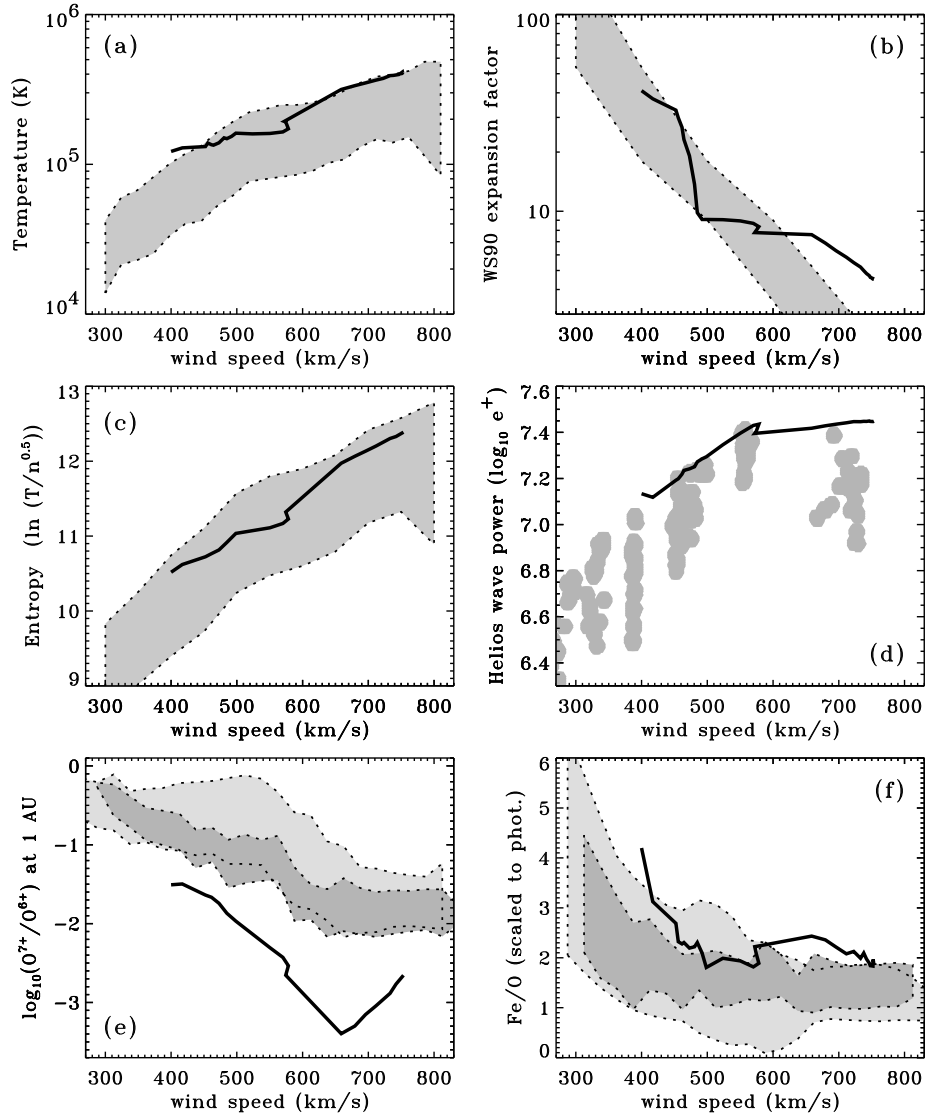


Fig. 1 Comparisons between the ZEPHYR models (thick black curves) and observational data in the solar wind (gray regions). See the main text for details (see also Cranmer et al. 2007; Cranmer 2009). In all panels except (d), the gray regions show the data binned by solar wind speed, showing only the regions within ± 1 standard deviation of the mean value at each speed.

However, the more recent 2008–2009 minimum has been seen to be quite different. Cranmer et al. (2010) produced a new ZEPHYR model of the fast polar wind that used a lower magnetic field consistent with both solar-disk and *in situ* measurements taken during 2008–2009. The model produced changes in the plasma properties at 1 AU that agree well with *Ulysses* measurements (e.g., McComas et al. 2008). For example, in both the models and the measurements, the wind speed u remains relatively unchanged, but the density n and temperature T decrease by factors of order 20% and 10%, re-

spectively. The decreases in gas pressure (proportional to nT) and dynamic pressure (proportional to nu^2) are between 20% and 30% for both the observations and models.

3. The *Helios* probes measured Faraday rotation fluctuations (FRFs) of polarized radio signals that passed through the solar corona at heliocentric impact parameters between 2 and 15 R_\odot in the ecliptic plane. The magnitude of these fluctuations depends not only on the amplitude of the Alfvén waves in the corona, but also on the density and the turbulent correlation length. Hollweg et al. (2010) compared the measured FRFs with predicted values from ZEPHYR, and found excellent agreement when using the equatorial streamer model originating at a colatitude of 28° .

4 Reconnection/Loop-Opening Models

It is clear from observations of the Sun’s highly dynamical “magnetic carpet” that much of the coronal heating in closed-field regions is driven by the interplay between the emergence, separation, merging, and cancellation of small-scale flux tubes. Magnetic reconnection seems to be the most likely channel for the built-up magnetic energy to be converted to heat (e.g., Priest and Forbes 2000). Thus, the RLO idea has a natural appeal since all open flux tubes are rooted in the vicinity of closed loops (Dowdy et al. 1986). In fact, isolated RLO-like reconnection events are already observed in coronal holes as *polar jets* by *SOHO* and *Hinode* (e.g., Wang et al. 1998; Shimojo et al. 2007). Also, there are observed correlations between the lengths of coronal loops, the electron temperature in the low corona, and the wind speed at 1 AU (Gloeckler et al. 2003) that are highly suggestive of a net transfer of magnetic energy from the loops to the open-field regions (see also Fisk et al. 1999; Fisk 2003).

Testing the RLO idea using theoretical models seems to be more difficult than testing the WTD idea because of the complex multi-scale nature of the relevant magnetic topology. It could be argued that one needs to create three-dimensional and time-dependent models of the magnetic carpet in order to fully take account of all interactions between the closed and open flux systems. Several key questions remain to be answered. For example, how much of the magnetic energy that is liberated by reconnection goes into simply reconfiguring the closed fields, and how much goes into changing closed fields into open fields? Specifically, what is the actual *rate* at which magnetic flux opens up in the magnetic carpet? Can the observed polar jets provide enough energy to drive a significant fraction of the solar wind? Lastly, how is the reconnection energy distributed into various forms (e.g., bulk kinetic energy, thermal energy, waves, or energetic particles) that can each affect the accelerating wind in different ways?

Recent work has started to provide tentative answers to some of the above questions. Cranmer and van Ballegoijen (2010) developed Monte Carlo simulations of the time-varying magnetic carpet and its connection to the large-scale coronal field. These models were constructed for a range of different magnetic flux imbalance ratios—i.e., for both quiet regions and coronal holes. The models agree with observed emergence rates, surface flux densities, and number distributions of magnetic elements. Despite having no imposed supergranular motions in the models, a realistic network of magnetic “funnels” appeared spontaneously as the result of diffusion-limited aggregation from smaller magnetic concentrations. Cranmer and van Ballegoijen (2010) computed the rates at which closed field lines open up (i.e., the recycling times for open flux), and they estimated the energy fluxes released in reconnection events that involve the opening up of closed flux tubes. For quiet regions and mixed-polarity coronal holes, these energy fluxes were found to be significantly smaller than

those required to accelerate the solar wind. In other words, only a tiny fraction of the Poynting flux delivered into the corona by emerging bipoles seems to be released via magnetic reconnection in RLO-like events. On the other hand, for the most imbalanced (i.e., unipolar) coronal holes, the energy in flux-opening events may be large enough to power the solar wind. However, in those cases the overall recycling times are far longer than the time it takes the solar wind to accelerate up into the low corona. Thus, RLO processes on supergranular scales may be responsible for the intermittent jets in coronal holes, but probably not for the majority of the “bulk” solar wind acceleration.

5 Conclusions

Despite recent progress made with both the WTD and RLO approaches to plasma heating and acceleration, we still do not have conclusive answers about whether one idea or the other is dominant in the actual corona and solar wind. It is possible, of course, that qualitatively different mechanisms may govern the heating and acceleration in different types of solar wind streams. It is also possible that some kind of combination of the WTD and RLO paradigms may be more valid than either idea in isolation.

An important next step in the process is to determine what specific observations can best test these ideas, with the goal of convincingly verifying and/or falsifying them. Also, a related future step will be to build three-dimensional models of the Sun-heliosphere system that include WTD and RLO physics as their “coronal heating functions.” These kinds of simulations can be customized for specific time periods, and be used to make straightforward comparisons with various kinds of existing remote-sensing and *in situ* measurements. Some recent progress in producing computationally efficient approximations to the rates of WTD wave reflection and heating has been reported by Chandran and Hollweg (2009) and Cranmer (2010).

In addition to expanding the scope of the models, it will also be important to develop a better understanding of the physics of MHD wave generation, propagation, and dissipation. Recent observations of Alfvén waves in the complex lower atmosphere indicate that the energy in fluctuations is distributed intermittently between spicules, loops, and the open-field corona (De Pontieu et al. 2007; Tomczyk et al. 2007; Tomczyk and McIntosh 2009; Fujimura and Tsuneta 2009). Magnetic flux tubes that thread the upper chromosphere and low corona support a wide range of possible nonlinear couplings between compressible and incompressible modes (e.g., Bogdan et al. 2003; Hasan et al. 2005). For example, acoustic waves from non-magnetic regions of the chromosphere may encounter a swaying flux tube and be converted into Alfvén or fast-mode waves as they pass through the tube. The study of energy transport across small-scale *interfaces* in the solar atmosphere may be crucial to producing more accurate and predictive models.

Finally, it is important for future models to take account of the kinetic and multi-fluid nature of coronal heating and solar wind acceleration (Marsch 2006). In the WTD paradigm, for example, a description of the large-scale energy flux injected into a turbulent cascade is only the first chapter in the story. Better descriptions of the anisotropic cascade process, the eventual kinetic dissipation of the fluctuations, and the subsequent energization of electrons, protons, and heavy ions are needed to complete the picture. Remote-sensing measurements of strong preferential heating and acceleration for heavy ions (e.g., O^{+5}) in coronal holes have spurred a great deal of theoretical work in this direction (see, e.g., Hollweg and Isenberg 2002; Cranmer 2002, 2009). A proper accounting of these kinetic effects will lead to more concrete predictions for measurements to be made by space missions

such as *Solar Probe* (McComas et al. 2007) and *Solar Orbiter* (Marsden and Fleck 2007), as well as next-generation ultraviolet coronagraph spectroscopy that could follow up on the successes of the UVCS instrument on *SOHO* (Kohl et al. 2006, 2008).

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